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Title:
OPTICAL AMPLIFIER

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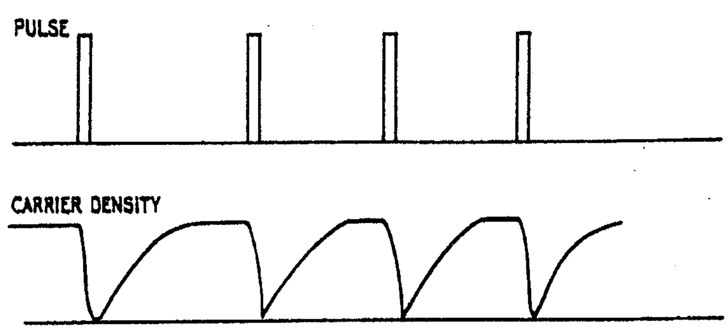

(57) Abstract

A laser amplifier operable such that at the commencement of each output pulse the carrier level has recovered from depletion by the previous pulse. Under these conditions output power commensurate with a much higher carrier density than is usually available is possible. The mode of operation is especially useful as a way of providing high power pulses, for example for use in optical time domain reflectometry. Using a travelling wave amplifier in conjuction with return to zero format data pulses is also disclosed.

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OPTICAL AMPLIFIER

This invention relates to optical amplifiers.

Laser amplifiers are of great interest as components in optical communication systems. Unfortunately, the devices suffer from output power saturation at relatively low power, that is in the range of 1 to 10 mW mean power.

There are also various applications for which it is desirable to have high power optical pulses, but at present the equipment necessary to provide such pulses is both expensive and bulky.

The present invention is directed towards obtaining relatively high power optical pulses from laser amplifiers, and in preferred embodiments towards providing portable high power optical sources.

Accordingly the present invention provides an optical amplifier operated such that at the commencement of each output pulse the carrier density in the amplifier has substantially recovered from depletion by the preceding output pulse enabling the output power to be increased to a level commensurate with the carrier density.

In another aspect the invention provides an optical amplifier arranged to provide a pulsed output with the interval between pulses being at least half the time required for substantial recovery of the carrier density from depletion by the preceding output pulse and enabling the output power to be increased to a level determined by the recovered carrier density.

Preferably the amplifier is a travelling wave amplifier. The term 'optical' as used herein includes those portions of the electromagnetic spectrum termed 'infra red', visible and 'ultra violet'.

The invention is now described by way of example with reference to the accompanying drawings in which:

Figure 1 shows carrier density versus time in a semiconductor laser amplifier;
Figure 2 shows a gain characteristic for a travelling wave amplifier;
Figure 3 is a schematic diagram of an embodiment of the invention, and
Figure 4 shows input versus output power for a laser amplifier operated in accordance with the invention.

Semiconductor laser amplifiers have heretofore been regarded as limited in output power to the order of 1 to 10 mW, and this limitation has been accepted in known applications of the device. However, the present invention is based upon a consideration of the instantaneous carrier concentration available and operation of the device so as to increase or maximise the carrier concentration at the moment of power output demand.

In a semiconductor laser the optical power output is limited by the internal carrier density as it is these carriers that produce the output power by electron-hole recombination in response to the input light signal. The carrier density is a function of the applied bias current, but there is a limit to the current that can be applied because for wideband operation the laser amplifier needs to be operated short of the lasing threshold, typically the bias being 70% of the lasing bias threshold. In the absence of an input light signal the carrier density is static at a level determined by

the bias, but as soon as a signal is input that stimulates recombination there is a resultant drop in the carrier concentration. The bias current regenerates carriers but the effect is not instantaneous so that under conditions of sustained input signal (which may be continuous or rapidly repeating pulses such as a run of binary ones) the carrier level remains depleted below the starting level, and steady state operation can only be sustained at a power level based on the carrier concentration in the depleted state. When input signal light is removed the carrier concentration builds up to the original starting level. The time taken for the original starting level to be regained is in general equal to the mean carrier recombination time or lifetime (although optical pumping or bias modulation may vary the parameters). The expression 'recovery time' is used herein to define the time taken for the carrier concentration to be restored to the undepleted level determined by the prevailing bias voltage when there is no input signal. Typically the recovery time may be of the order of 2ns.

Figure 1 shows schematically carrier density versus time in a semiconductor laser amplifier for various excitation conditions. In Figure 1a there is first zero input signal, followed by a series of pulses, then an absence of signal followed by a single long pulse. This sequence could easily correspond to a data signal of binary zeros and ones with the absence of signal representing one or more zeros and the single long pulse being a run of consecutive ones. Under these conditions it can be seen that the carrier density rarely returns to the undepleted level 1; in general the carrier concentration is at a much lower level 2 and it is this lower level that determines the output power. It is not possible to utilise the occasional availability of higher carrier densities because these appear unpredictably (for example only after a sequence of zeros) and cannot be sustained. These are the conditions under which laser

amplifiers have been used and illustrates how the accepted limitation arises.

In contrast, in Figure 1b narrow pulses spaced apart by a distance sufficient to enable substantial recovery of the original carrier density means that the power available for each pulse is based upon the higher carrier density. This is the principle mode of operation according to the invention.

As an intermediate step between conventional operation and that shown in Figure 1b, incomplete carrier density recovery, but still greater than that permitted by conventional operation, may be provided as shown in Figure 1c. In this instance intermediate pulse powers are achieved. Use of return to zero data pulses and a narrow pulse width enable much higher powers to be achieved than previously, as seen by comparing Figures 1a and 1c.

In order to achieve high power output from a laser amplifier, that is achieving output power commensurate with a carrier density substantially greater than that which leads to output power saturation under conventional operation, requires observation of the following criteria:

1. The input pulse should have a pulse width less than the recovery time of the amplifier, preferably substantially less.

2. The interval between pulses should permit substantial recovery to take place, preferably the interval should be greater than the recovery time.

3. If a data pattern is to be amplified the input should be in return to zero format to avoid runs of ones resulting in sustained depletion of carrier density.

It should be noted that when operating in its conventional mode the carrier density in a laser amplifier remains substantially constant from operational considerations, that is the output is taken with the carrier density depleted to the lower level. However, the mode of operation according to the invention takes the output during a period of considerable change in carrier density, essentially during the drop from the maximum to minimum carrier densities, and this change in carrier concentration causes, in presently available materials, a change in the refractive index of the device medium, which results in wavelength shifts in the amplifier spectrum. Figure 2 shows (in full lines) the characteristics of amplifier gain versus wavelength for a Fabry Perot laser amplifier from which it can be seen that wavelength shift can have a dramatic effect on amplifier gain. The dotted line in Figure 2 shows the characteristic for a travelling wave or near travelling laser amplifier in which the gain fluctuation with wavelength is much reduced. For most practical purposes a gain ripple amplitude of about 3dB at the mean operating wavelength is tolerable (although in some instances 6dB or more may be acceptable), and so a fourth criterion of operation with carrier density sensitive material in the high-power amplification mode of the invention is the use of a travelling wave or near travelling wave amplifier, for example by provision of antireflection coatings on one or more of the laser facets. In this specification 'travelling wave amplifier' is used to denote amplifiers of the type in which this gain ripple is eliminated or suppressed and includes amplifiers of the type termed 'near travelling wave amplifiers'.

Within these constraints the pulse output can be made of higher peak power and shorter duration or of longer duration with lower power. If P_p is the peak output power, P_s the mean output saturation power, T_r the repetition time and T the pulse width it has been found that the following

approximate relationship holds approximately for non extreme values.

$$P_p = (T_r/T)\ P_s$$

A practical embodiment utilising the above described mode of operation of a laser amplifier is shown schematically in Figure 3. A primary optical pulse source 3 has its output input to a pulse processor 4 and the pulse processor output is input to the laser amplifier 5. The pulse 3 source and pulse processor may be any components that provide pulses of suitable length and repetition frequency. For example the pulse source may be another laser that is mode locked, from which a stream of pulses of relatively high repetition rate is obtained with the pulse processor blocking most of the pulses so that only every n th pulse is selected and reaches the laser amplifier. Alternatively a source such as a constricted mesa laser may be electrically pulsed to provide pulses of suitable repetition rate, but these are too long in pulse length and so the pulse processor is then a pulse compressor. Another method of providing a suitable pulse source is to gain switch a laser source; the output of this process will usually require both pulse blocking or selection and pulse compression processing. Other possible sources are gas lasers with optical switches, solid state lasers such as iodine lasers and fibre lasers which may be mode locked or Q switched.

A suitable laser amplifier 5, for example is a 1.5 microns DCPBH laser of 500 microns cavity length with antireflection coatings on both facets. The coatings may be single layer refractory oxide coatings to provide low facet reflectivities, for example of the order of 0.08% or less. With a pulse source and processor providing a pulse repetition T_r of 10 ns a device with a peak saturation power P_s of 1 mW achieved a peak pulse power of 250 mW for a pulse

width of 40ps; a device with a peak saturation power of 10 mW yielded, for the same pulse period, 2.5W. As the pulse repetition time T_r increases, the peak power increases until limited by other factors such as laser facet damage. Increasing the pulse width causes decay of the trailing part of the pulse when power cannot be sustained for the full pulse, this effect becoming evident at pulse widths of the order of 1-2ns. Figure 4 shows peak input power versus peak output power for the 1.5 microns DCPBH laser biased at 70% of the lasing threshold. In general it is preferred to operate travelling wave laser amplifiers at about 70% of the lasing threshold; at higher biases the ripples in the amplification tend to increase (eg 6dB at 95% of lasing bias compared to 3dB at 70%) and the bandwidth of the amplifier decreases.

For data applications in which a return to zero format is used for the data a non-standard format is preferably adopted in which the pulse representing binary one occupies only a small proportion of the bit period. For recovery times of 1 ns data rates of 1Gbit/sec are possible, the pulse format providing greater receiver sensitivity and hence system performance.

It will be realised that when using a portable primary pulse source such as a semiconductor laser, the laser amplifier operated according to the invention provides a portable and comparatively inexpensive high power pulse source. A particularly important use of such a source is in optical time domain reflectometry (OTDR) in which a pulse of light is launched into a fibre that is to be surveyed for faults and any light returning due to reflection at faults is analysed in order to locate the fault. In this technique the length of fibre that can be surveyed is determined by the sensitivity of the detector and the energy of the pulse that is launched. For high resolution measurements, that is to survey accurately to within centimetres, pulse widths of the

order of 100ps (more generally the range may be 10 to 200ps) are required. The present invention provides a possible increase of 20dB in input energy thus enabling either use of less sensitive detectors or survey of a greater length of fibre. For use in the field the portability of the equipment is of significant value.

There are various other uses for a high power optical pulse source, especially in non-destructive testing techniques such as medical diagnostics. One technique currently under development is the monitoring of the concentration of oxygen in the brains of premature babies by high power pulses at infa-red wavelengths. At 1.3 or 1.5 microns the absorbtion of light by tissue (principally water) is low but absorbtion by other materials (like oxygen molecules) is high, so tests can be made through entire organs rather than needing to take a section. However in order to have enough power to provide measurements without causing burning, the source must be pulsed at high speed. Currently the available sources (dye lasers) are not portable however a source based on this invention is easily portable, enabling bedside installation and operation and is capable of providing comparable power.

A particularly preferred pulse format is for the pulse to occupy at most one tenth of the pulse interval and for the pulse interval to be of the order of at least two or three times the recovery time.

CLAIMS

1. An optical amplifier operable such that at the commencement of each output pulse the carrier density in the amplifier has substantially recovered from depletion by the preceding output pulse enabling the output power to be increased to a level commensurate with the carrier density.

2. An optical amplifier arranged to provide a pulsed output with the interval between pulses being at least half the time required for substantial recovery of the carrier density from depletion by the preceding output pulse and enabling the output power to be increased to a level determined by the recovered carrier density.

3. An optical amplifier according to claim 1 or claim 2 in which the amplifier is a travelling wave amplifier .

4. An optical amplifier according to claim 3 in which the gain ripple is at most 3dB.

5. An optical amplifier according to any preceding claim in which the output pulse duration is at most one half of the time required for recovery of the carrier density.

6. An optical amplifier according to any preceding claim in which the output pulse duration is at most one third of the time required for recovery of the carrier density.

7. An optical amplifier according to any preceding claim in which the interval between output pulses is at least equal to the time required for recovery of the carrier density.

8. An optical amplifier according to any preceding claim arranged to receive input data in return to zero format.

9. An optical amplifier according tc any preceding claim in which the amplified output pulses comprise a return to zero format data stream.

10. An optical amplifier according to claim 8 or claim 9 in which the return to zero data format comprises signal pulses of a duration less than half of the bit period.

11. An optical amplifier according to claim 10 in which the pulses are at the leading edge of the bit period.

12. An optical amplifier according to any of claims 8 to 11 in which the bit period is of a duration at least equal to the time required for recovery of the carrier density.

13. An optical pulse source comprising an optical amplifier according to any preceding claim in combination with an optical pulse source and a pulse processor arranged to input pulses to the amplifier with a pulse duration substantially less than the carrier density recovery time of the amplifier and a pulse interval at least substantially equal to the carrier density recovery time of the amplifier.

FIG. 1a

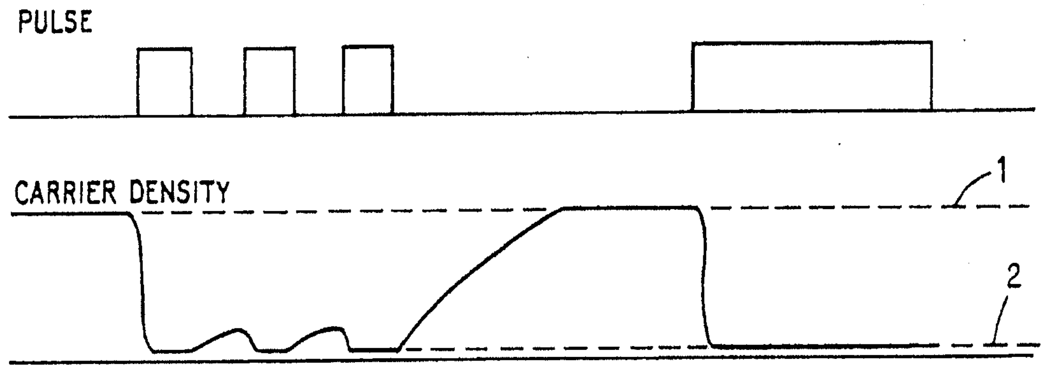


FIG. 1b

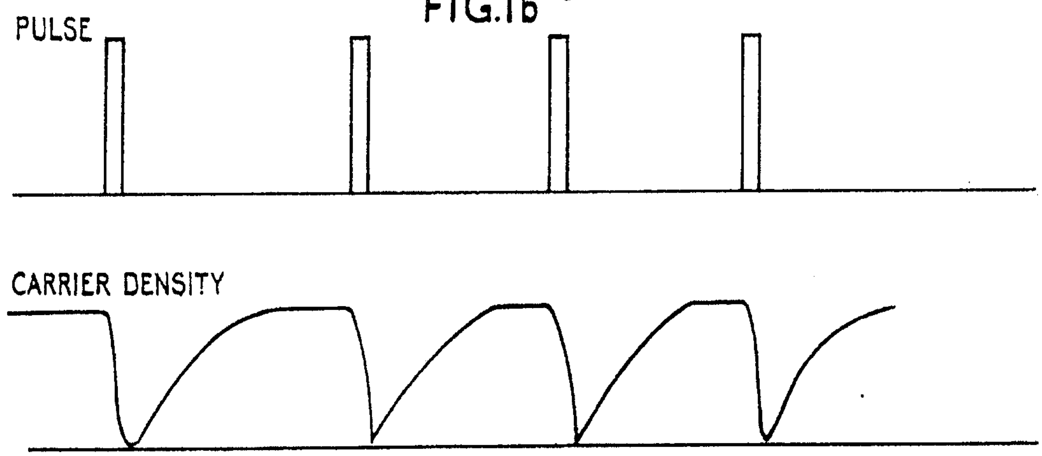


FIG. 1c

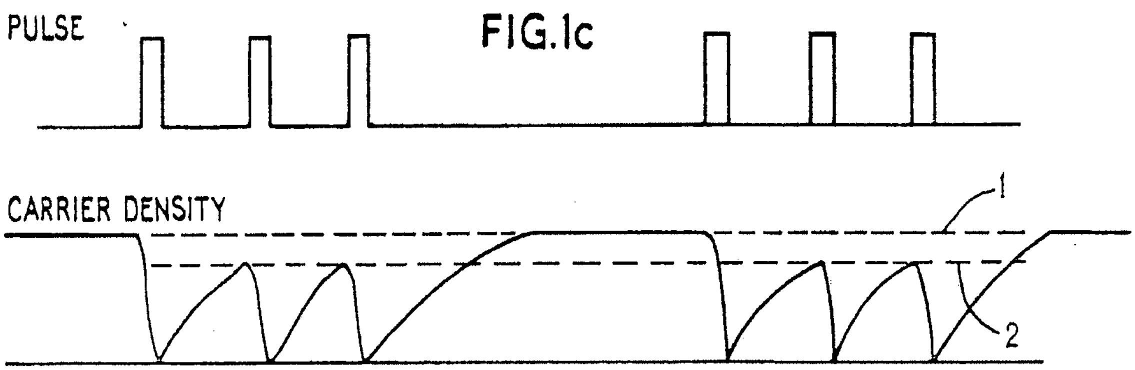


FIG. 2

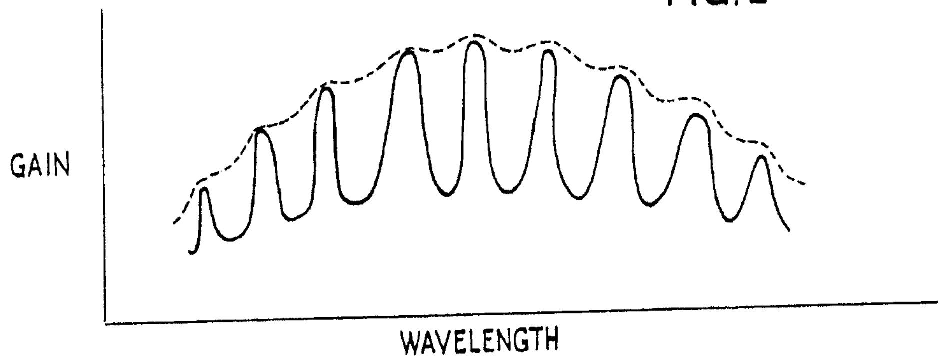


FIG. 3

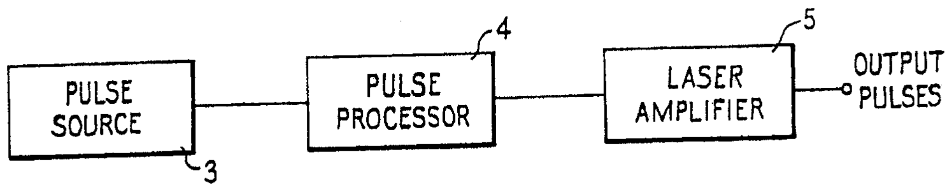
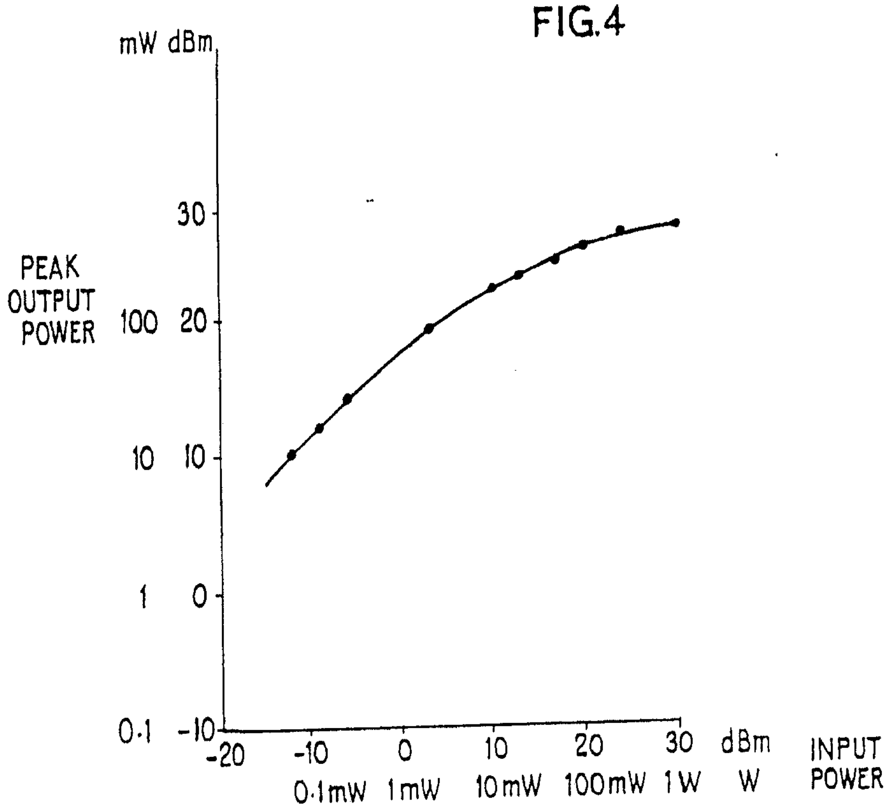


FIG. 4



INTERNATIONAL SEARCH REPORT

International Application No PCT/GB 88/00280

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [6]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC^4: H 01 S 3/23

II. FIELDS SEARCHED

Minimum Documentation Searched [7]

Classification System	Classification Symbols
IPC^4	H 01 S

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [9]

Category *	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No. [13]
A	Applied Physics Letters, volume 45, no. 12, 15 December 1984, American Institute of Physics, (New York, US), J. Hegarty et al.: "High-speed modulation and switching with gain in a GaAlAs traveling-wave optical amplifier", pages 1314-1316 see page 1314 --	1,3
A	EP, A, 0174729 (BRITISH TELECOMMUNICATIONS) 19 March 1986 see abstract; page 5, lines 4-18; page 6, lines 8-23; page 7, lines 2-11	1

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* Special categories of cited documents: [10]

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"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
30th June 1988	19 JUL 1988
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	P.C.G. VAN DER PUTTEN

Form PCT/ISA/210 (second sheet) (January 1985)

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL PATENT APPLICATION NO. GB 8800280

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The members are as contained in the European Patent Office EDP file on 07/07/88
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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP-A- 0174729	19-03-86	JP-A- 61105887	23-05-86
		US-A- 4736164	05-04-88

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